SEARCH FOR ^{44}TI GAMMA-RAY LINE EMISSION FROM GRO J0852-4642 WITH INTEGRAL/SPI

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ABSTRACT

The gamma-ray source GRO J0852-4642, discovered by COMPTEL, is a possible counterpart of the supernova remnant RX J0852-4622. Detection of radioactive decay from ^{44}Ti nuclei would proof it to be the youngest and nearest supernova remnant known so far. During the first year of *INTEGRAL* core program, the Vela region was observed twice in all for more than 2000 ks. Among other nucleosynthesis studies, one of the most important scientific goals of this observation is the detection of ^{44}Ti gamma-ray lines expected at 68 keV, 78 keV and 1157 keV. For this purpose the *INTEGRAL* Spectrometer (SPI), with its very high energy resolution thanks to its germanium detector camera is the key instrument, permitting a precise determination of gamma-ray line intensities and profiles. The upper limit for the 78.4 keV ^{44}Ti gamma-ray line emission derived from the first analysis is $1.1 \times 10^{-4}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This value is mainly dominated by systematic uncertainties in the treatment of the instrumental background. By accumulating more observation time in the next years of the mission and by improving the background understanding, a reliable ^{44}Ti flux for GRO J0852-4642 or an upper limit which constrains the COMPTEL flux can be expected.

Key words: gamma rays: observations, nucleosynthesis, Space telescope: SPI/INTEGRAL.

1. INTRODUCTION

One of the main scientific topics of the *INTEGRAL* mission is the investigation of stellar nucleosynthesis (Hydrostatic burning, supernovae, novae) (Winkler et al. 2003). In this context the spectrometer SPI is important, due to its capability to resolve nuclear lines with its high energy resolution (Vedrenne et al. 2003; Schanne et al. 2003; Attié et al. 2003). The measurement of γ-ray line intensities, line profiles and line shifts is one of SPI's main goals (Schönfelder et al. 2000).

Only few isotopes exist which are accessible to γ-ray astronomy for probing cosmic nucleosynthesis (Diehl & Timmes 1998). Especially ^{44}Ti is an important probe for the investigation of supernovae (SNe) and their young remnants (SNR). ^{44}Ti decays via ^{44}Sc to ^{44}Ca:

$$^{44}\mathrm{Ti}\left[\frac{67.9\,\mathrm{keV},\,78.4\,\mathrm{keV}}{\tau = 86.0 \pm 0.7\,\mathrm{yr}}\right] \rightarrow\ ^{44}\mathrm{Sc}\left[\frac{1157.0\,\mathrm{keV}}{\tau = 5.67\,\mathrm{h}}\right] \rightarrow\ ^{44}\mathrm{Ca}$$

This decay chain is driven by the decay-time of ^{44}Ti. The 67.9 keV and 78.4 keV transitions form a cascade and have the same probability (99%) as the 1157 keV transition, thus a similar flux of all three lines is expected. The mean life-time of ^{44}Ti was for a long time very uncertain, but has been settled a few years ago to a current "best value" of 86.0 ± 0.7 yr (1 σ error) [half-life time: 59.6 ± 0.5 yr], from more accurate laboratory measurements (Norman et al. 1998; Ahmad et al. 1998; Görres et al. 1998; Wietfeldt et al. 1999). ^{44}Ti decays through electron capture, therefore its decay lifetime depends on the ionization state: in the extreme case of a fully-ionized nucleus the ^{44}Ti isotope is stable. This effect, if present, might introduce some uncertainty in the estimation of the ^{44}Ti-mass ejected by the SN (Mochizuki et al. 1999; Laming 2001).

The discovery of 1157 keV ^{44}Ti line emission from the historic youngest-known Galactic SNR Cas A by COMPTEL (Iyudin et al. 1994) confirmed that ^{44}Ti is indeed produced in core collapse SNe explosions. ^{44}Ti is expected to be produced in all types of SNe, although with very different yields, depending on the mass-cut between a few 10^{-5} and 10^{-4} $M_\odot$ for the most frequent SNe of type II and Ib (Woosley & Weaver 1995; Thielemann et al. 1996). ^{44}Ti provides an excellent diagnostic of the still not completely understood core-collapse SN-explosion mechanism itself. According to theoretical models, ^{44}Ti is produced through explosive Si burning in an α-rich freeze-out and thus originating from the inner-

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most ejected material. ^{44}Ti thus probes deep into the interior of the exploded star (similar to radioactive ^{56}Ni). Its yield is sensitive to the asymmetries of the collapse and explosion, possibly caused by stellar rotation (Nagataki et al. 1998).

The recently-discovered SNR RXJ0852-4622 (Aschenbach 1998), with $\sim 2°$ diameter, an age probably much below that of the Vela SNR, and a large distance uncertainty, from 0.2 to 1 kpc, is the object of our investigation. *INTEGRAL* observations have the potential to resolve the distance uncertainty from a test for ^{44}Ti emission and from a study of the 1.8 MeV gamma-ray line shape expected to be broadened and produced by the decay of fast moving ^{26}Al nuclei possibly released by this SNR, compared to the line shape (narrow) produced by slow moving ^{26}Al nuclei which form a diffuse background in the Vela region.

The flux of the ^{44}Ti line is given by

$$\Phi = \frac{1}{4\pi \cdot d^2} \cdot \frac{Y_{\rm Ti}}{m_{\rm Ti} \cdot \tau_{\rm Ti}} \cdot e^{-\frac{t}{\tau_{\rm Ti}}}, \qquad (1)$$

with d as the distance of the supernova, $Y_{\rm Ti}$ as the mass yield of ^{44}Ti, $m_{\rm Ti}$ as the atomic mass of ^{44}Ti, $\tau_{\rm Ti}$ as the ^{44}Ti mean life-time and t as the time elapsed since the supernova explosion. Obviously, for any observed flux there is some ambiguity in the age and distance parameters of the source. This is where other astronomical observations must join in. Ice-core dating of nearby supernovae had been proposed for such purpose already in the 1970s. It was claimed that the measurement of nitrate abundance in Antarctic ice cores shows evidence for a correlation with known recent nearby supernovae (Rood et al. 1979; Burgess & Zuber 2000), due to photochemical reactions in the atmosphere.

From the observations of X-rays, the age and distance of the newly-discovered SNR RXJ0852-4622 has been a matter of debate. From its size and spectrum, values well below 1 kpc were thought plausible (Aschenbach 1998), while comparisons of absorption column data with the Vela SNR require distances well beyond the Vela SNR (currently placed at 250 pc; Cha et al. (1999); Slane et al. (2001)). From an identification of RXJ0852-4622 with the ^{44}Ti source, a combination of arguments led to a most plausible parameter set of 200 pc for the distance, and 680 years for the age of the SN (Aschenbach et al. 1999). Other tracers (Iyudin 2002) also support a SN event around 1320, the occurance time of the COMPTEL GRO J0852-4622 event estimated from ^{44}Ti measurements (Iyudin et al. 1998). If this small distance value applies, an interesting perspective for *INTEGRAL* is opened from its capability to detect ^{26}Al radioactive isotopes expected to be released by this SNR. Indeed, core-collapse supernovae are believed to be common sources of ^{26}Al (Prantzos & Diehl 1996), and could be visible with *INTEGRAL* as individual sources out to distances of a few 100 pc, assuming standard model yields, due to the long ^{26}Al lifetime of $\sim 10^6$ y. Indeed, COMPTEL's ^{26}Al survey shows a peak of emission towards this direction, which could be largely due to this source (Aschenbach et al. 1999). First results of a search for ^{26}Al emission in the Vela region with *INTEGRAL*/SPI are shown elsewhere (Maurin et al. 2004). A measurement of the ^{26}Al line width in the Vela region, expected to be performed by SPI, will be crucial for the interpretation of the nature of the SNR RX J0852-4622.

The detection of 1157 keV ^{44}Ti emission (Iyudin et al. 1998) has shown that it is possible to discover a supernova remnant, which was undetected in other wavelengths before, by the detection of γ-ray lines. Although the ^{44}Ti detection is only marginal (Schönfelder et al. 2000), it is for the first time that a γ-ray line observation triggered the discovery of a new supernova remnant, through X-rays measured with ROSAT. A confirmed ^{44}Ti γ-ray line emission for GRO J0852-4642 will help also to study the Galactic supernovae rate. ^{44}Ti is an excellent indicator for Galactic supernova explosions which occurred in the past few centuries (age $\leq$ 1000 yr), even in otherwise obscured regions. The Galaxy is, compared to other wavelength bands, practically transparent in the γ-ray band. Therefore it will be possible to complement historical observations of galactic SNe through supernovae remnants revealed by their ^{44}Ti γ-ray line emission.

2. OBSERVATION OF THE VELA REGION

The Vela Region was observed twice during the *INTEGRAL* AO-I Core Program in 2003.

The first set of data with 1236 ks exposure time was recorded during the satellite orbits 81 to 88 from June 12 until July 6. The 5×5 dither pattern was centered in the Vela region at $\alpha_{\rm J2000} = 8^{\rm h}\,52^{\rm m}\,45.6^{\rm s}$ and $\delta_{\rm J2000} = -44°\,35'\,07.2"$, $\sim 2°$ off the position of the potential SNR GRO J0852-4642. During orbit 82 and 83 a large solar flare occurred with the consequence that the data of these orbits were left out for the analysis.

The second set of data with 986 ks exposure time has been taken during the orbits 137 to 141 from November 27 until December 11. The 5×5 dither pattern was centered on $\alpha_{\rm J2000} = 8^{\rm h}\,27^{\rm m}\,54.7^{\rm s}$ and $\delta_{\rm J2000} = -46°\,18'\,18.4"$, $\sim 4°$ off the position of GRO J0852-4642. In reaction to the Vela X-1 outburst on November 28 (Krivonos et al. 2003; Staubert et al. 2004), a 12.6 ks observation with a hexagonal dither pattern centered on Vela X-1 ($\alpha_{\rm J2000} = 9^{\rm h}\,2^{\rm m}\,6.9^{\rm s}$ and $\delta_{\rm J2000} = -40°\,33'\,7.2"$) was executed end of orbit 138 on December 2. Unfortunately one of SPI's germanium detectors (Ge-detector No. 2) failed at the beginning of orbit 140 on December 6. The consequence is that the partly energy deposition in detectors which are involved in the same multiple detector event as the failed one will impose fake background events, especially in detectors which are located in

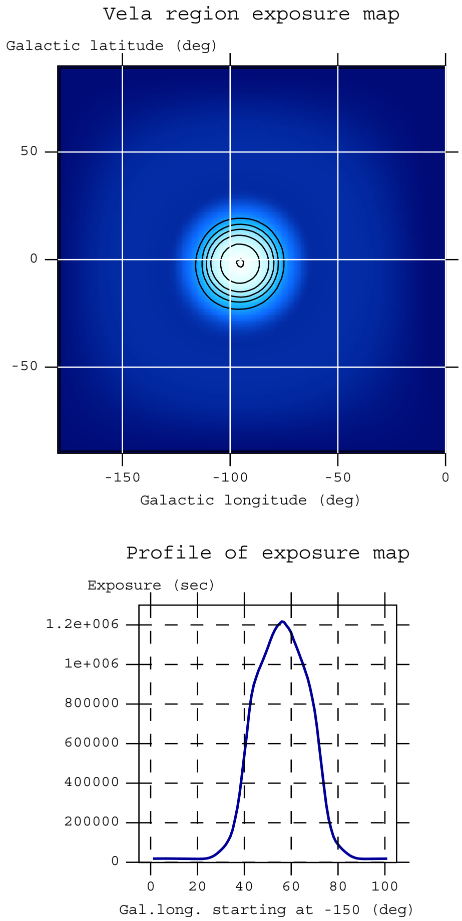

Figure 1. Distribution map of the effective exposure of the Vela region. The location of GRO J0852-4642 coincides approximately with the maximum exposure of about 1200 ks.

the neighborhood of Ge-detector 2. A new detector response is required to account for the changed conditions. The current analysis, which is presented here, discards the data of orbit 140 and 141 until the new response is available. As it already happened during the first Vela observation, a strong solar flare occurred during the second period too, starting at the end of orbit 138 and lasting until the beginning of orbit 139. Due to the shorter duration of the activity, the recorded data were used for the analysis.

Altogether the Vela Region was observed for 2235 ks. The data of the orbits 82, 83, 140, 141 and the satellite slews were discarded. Thus the on-target time used for the analysis amounts 1540 ks. With the mean deadtime of all detectors and pointings of $\sim$ 11% the effective exposure was 1370 ks. Fig. 1 shows the distribution map of the effective exposure. With the selected data, only 1200 ks effective exposure (about 54% of the observing time) are available for the spectral analysis of GRO J0852-4642.

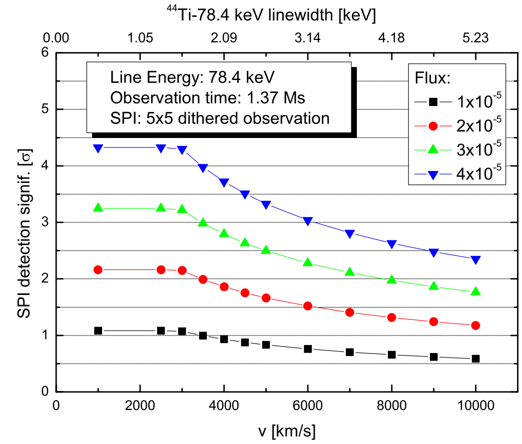

Figure 2. Expected detection significances for the ^{44}Ti-line at 78.4 keV for source fluxes ranging from 1 to 4 $\times 10^{-5}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Observation conditions for SPI are 1370 ks observation time and a 5×5 dither mode.

3. SENSITIVITY ESTIMATIONS

The expectations to obtain a significant result for the 67.9 keV line is low, because SPI has at 67.9 keV a small sensitivity of $\mathrm{F}_{67.9} \approx 7\times10^{-5}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ caused by the strong background line complex between 50 and 70 keV (see Fig. 3). The narrow line sensitivity at the 1157 keV line is $\mathrm{F}_{1157} \approx 2.3\times10^{-5}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, when adding the single and multiple detector events, it is about the same as the one at 78.4 keV of $\mathrm{F}_{78.4} \approx 2.5\times10^{-5}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (sensitivities taken from Roques et al. (2003)). However at high energies SPI's sensitivity is deteriorated by strong Doppler line broadening which can be expected for this source. In the case of SPI the Doppler broadening of the 1157 keV line could exceed significantly the intrinsic energy resolution of the germanium detector, leading to a reduced sensitivity. For example a Doppler broadening of 35 keV, which corresponds to an expansion velocity of about 4600 km/s, only a significance of $\sigma = 1.4$ can be obtained with an 3000 ks observation.

Fig. 2 summarize the expected significances for the detection of the 78.4 keV ^{44}Ti-line with SPI for an 1370 ks observation with a 5×5 dither pattern ($\sim$16 days, which corresponds to the effective exposure as determined in Section 2). The significances were derived by using the Observation Time Estimator (OTE) of ISOC for ^{44}Ti-line fluxes in the range $F_{78.4\,\mathrm{keV}} = (1-4)\times10^{-5}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This range corresponds to the ^{44}Ti excess measured with COMPTEL of $F_{1157\,\mathrm{keV}} = (2-4)\times10^{-5}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ from GRO J0852-4642 (Schönfelder et al. 2000). The expected significances are plotted for expansion velocities of the SNR between 1,000 and $10,000\,\mathrm{km\,s}^{-1}$. Higher velocities lead to an even larger broadening of the line so that they fall below the sensitivity limit of

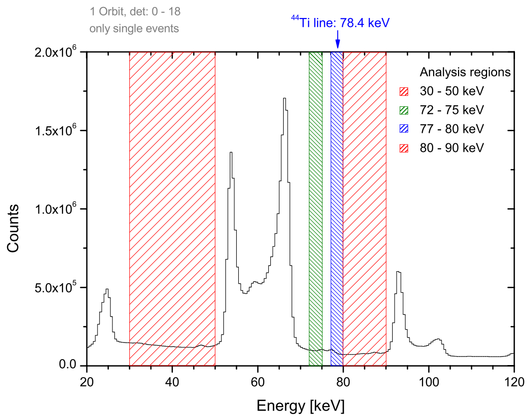

Figure 3. Low energy part of typical spectrum of SPI's germanium camera. The spectrum comprises data from one orbit with the single events of all 19 detectors summed up after the energy calibration.

SPI. A hexagonal dither pattern would have yielded a higher detection significance for the same observation time, but with the point source on axis, the equations which have to be solved for a SPI image reconstruction are underdetermined. So the SPI data would be of limited use.

In the case of a SN of type Ib/II ^{44}Ti is coming from the innermost ejected material. So it is expected that ^{44}Ti was ejected at lower speed compared to the mean expansion velocity of known SNR of about $4600\,\mathrm{km\,s^{-1}}$ (Hughes 2000). For a Doppler-broadened line with FWHM of 2.4 keV, which corresponds to an expansion velocity of about $4600\,\mathrm{km\,s^{-1}}$, the ^{44}Ti 78.4 keV line will be detectable at $\sim 3.5\,\sigma$ level for the highest flux depicted in Fig. 2. The instrumental energy resolution of the germanium detectors is about 1.8 keV in this energy range, thus it should be possible to determine/constrain the Doppler broadening and the shape of the line.

From IBIS/ISGRI interesting results can be expected (Lebrun et al. 2001), because it provides a high angular resolution of 12 arcmin, which is high enough to spatially resolve GRO J0852-4642, but with the drawback of a degraded sensitivity for sources which are not point like. Furthermore the energy resolution of ISGRI ($\Delta E/E$: 9% at 100 keV) is not sufficient to address a possible line broadening. Already from the AO-1 observation of the Galatic center region with ISGRI upper limits on the ^{44}Ti line flux at 67.9 keV and 78.4 keV are presented by Renaud et al. (2004). From IBIS/PICsIT we do not expect a significant result at 1157 keV, because its line sensitivity at this energy is more than an order of magnitude worse compared to that of SPI.

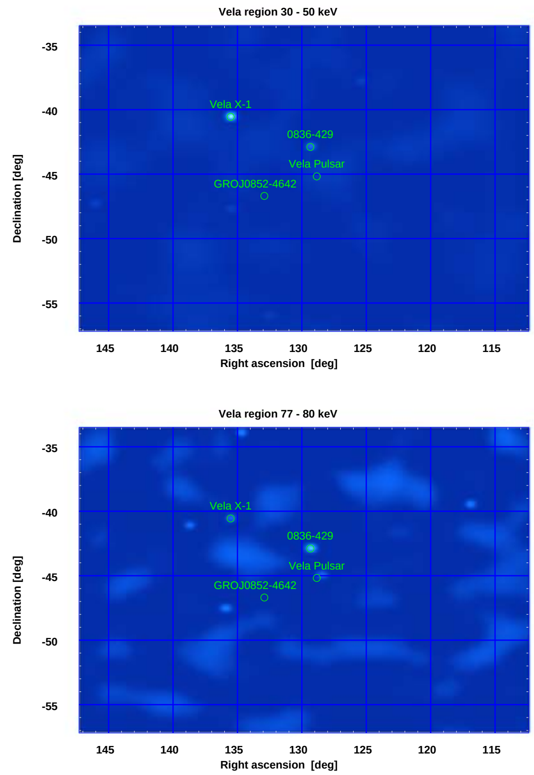

Figure 4. SPIROS significance maps of the Vela region for the 30 and 50 keV energy band (upper plot) and the 77 to 80 keV band (lower plot). The circles mark the positions of known sources.

4. ANALYSIS

As has been shown in Section 3 the search for an astrophysical ^{44}Ti-line flux is most promising at the 78.4 keV line, especially for broadened lines. The analysis method[1] uses imaging in a narrow energy band around this line from 77 to 80 keV. For an assessment of systematics and artefacts, the analysis was redone in an adjacent narrow energy band between 72 and 75 keV. In order to find strong continuum sources, which could produce fake line sources in the two narrow energy bands, a search for continuum sources was performed in two broader energy bands, lacking of strong background lines, one below the interesting range from 30 to 50 keV and one above from 70 to 80 keV. In Fig. 3 these four energy ranges are marked on top of a typical spectrum of SPI's camera.

The imaging analysis was performed by using the SPIROS[2] software (Skinner & Connell 2003). SPIROS allows the choice between different background models and methods. Commonly the saturated event rate of each germanium detector is used as a background tracer, which is a good measure of the high-energy particle flux impinging on SPI's

[1] The data were prepared with the *INTEGRAL* off-line scientific analysis package, version OSA 3.0, released by ISDC.
[2] SPIROS, version 6.0.

Table 1. Source fluxes extracted with SPIROS in imaging mode. The location of three sources were fixed by using an input catalog for SPIROS. The other sources were found freeely by SPIROS by searching for up to five new sources in the observed region. The four energy ranges used for the analysis were already presented in Fig. 3. Two of the corresponding significance maps of the Vela region are shown in Fig. 4

Source	Flux $[10^{-4}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}]$			
E - Range	"continuum" 30 – 50 keV	"line" 72 – 75 keV	"^{44}Ti - line" 77 – 80 keV	"continuum" 80 – 90 keV
	sources fixed:			
Vela X-1	145.5 ±0.7	0.6 ± 0.2	0.4 ± 0.2	1.4 ± 0.3
GS0836-429	46.04 ± 0.7	1.3 ± 0.2	1.2 ± 0.2	1.5 ± 0.3
GROJ0852-4642	–	–	0.0 ± 0.2	–
	free search for new sources:			
(Vela Pulsar)	–	–	0.4 ± 0.2	1.9 ± 0.3
"Spurious" detections up to	16 ± 0.7	0.6 ± 0.2	0.7 ± 0.2	1.1 ± 0.3

camera. This rate can be used as an estimate of the background variation with time and of the scaling factors between the detectors, which both will be fitted within SPIROS (SPIROS method 2). An alternative is the so called "mean count-rate method" (MCM: SPIROS method 5) which does not need a background model generated by another program like SPIBACK (Diehl et al. 2003). SPIROS is calculating in this case the background internally by assuming that the measured rates of each detector are mainly due to background events. Their variations are accounted for changes of the background level. This method is not advisable in the case when strong or variable sources are in the field of view. The χ^2 optimization statistics was used and pointings with extreme count residues above 3 σ for each detector individually were automatically excluded by SPIROS. With this method it is possible to obtain reduced χ^2 values ≤ 2. The Vela region was analyzed with both background methods. Nevertheless a strong and variable source was in the field of view (Vela X-1), the results obtained with the MCM background method (summarized in Tab. 1) yielded better χ^2 values.

The results of the imaging analysis are summarized in Tab. 1. In all 4 energy bands the position of three sources, Vela X-1, the Burster GS0836-429 (Aoki et al. 1992) and the source of interest GROJ0852-4642 were fixed. With SPIROS a search for 5 new sources above a significance threshold of 3 σ was performed and the fluxes of the fixed and newly found sources were extracted. Fig. 4 shows two of the obtained SPIROS detection significance maps. In both broad energy bands the two continuum sources Vela X-1 and GS0836-429 were detected. In the 30 to 50 keV band with a high significance $\sigma > 50$ and in the 80 to 90 keV band with $\sigma > 3$. In the two line-like energy bands only GS0836-429 was visible with $\sigma \geq 6$. The Vela Pulsar was found without catalogue input in the 80-90 keV energy band at $\sim 6\,\sigma$, 0.33° off the catalogue position. No flux was detected from GROJ0852-4642 in any of the 4 energy bands, especially in the energy band where the ^{44}Ti line flux is expected. In this case a statistical 2σ upper limit of $4 \times 10^{-5}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}$ can be deduced. In all four energy bands always 5 new sources, most of them obviously not real (except Vela pulsar), at random positions were found. The extracted flux levels of the strongest of these "spurious" sources is listed in the last row of Tab. 1. A detailed discussion on the detection of spurious sources can be found in Dubath et al. (2004)

The occurrence of spurious sources can be used as a measure of the systematic uncertainties introduced by a not optimal handling of the background. For the ^{44}Ti line energy band we detected spurious sources up to a flux of $7 \times 10^{-5}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}$. Adding the statistical 2σ upper limit, one gets a conservative upper limit for the ^{44}Ti line flux at 78.4 keV for GROJ0852-4642 of $1.1 \times 10^{-4}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}$.

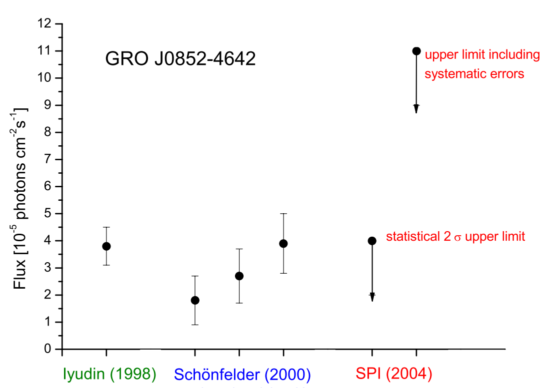

Figure 5. SPI upper limit in comparision to literature values for the ^{44}Ti line flux from GROJ0852-4642.

5. CONCLUSION

In Fig. 5 the upper limits derived from the current analysis of the SPI Vela observation are compared with flux values quoted for GROJ0852-4642 in the literature (Iyudin et al. 1998; Schönfelder et al. 2000). Without improving the systematic uncertainties the SPI result will not constrain the COMPTEL measurements.

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